Non-relativistic particles in a thermal bath

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Introduction

Heavy particles

Heavy particles are a window to new physics for they may be sensitive to new fundamental degrees of freedom. Some of these new degrees of freedom may be themselves heavy particles.
Ex. Heavy Majorana neutrinos.

Heavy particles can also be clean probes of new phenomena emerging in particularly complex environments.
Ex. Heavy quarks and quarkonia in heavy-ion collisions.

Scales

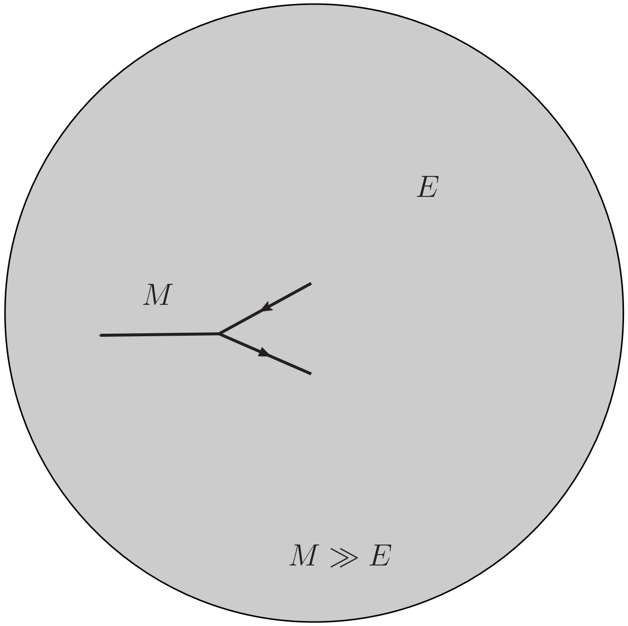
We call a particle of mass M heavy if

$$M \gg E \text{ (all other energy scales)}$$

This implies that the particle is non-relativistic.
It calls for an EFT treatment at a scale $M \gg \mu \gg E$.

Ex.:

- HQET
- (p)NRQCD, (p)NRQED
- HBET
- Electroweak EFTs for heavy quarks
- ...



Non-relativistic EFTs

The hierarchy $M \gg E$ allows describing the system at a scale $M \gg \mu \gg E$ in terms of a heavy-particle low-energy field H and all other fields that exist at the energy E.

The EFT Lagrangian reads

$$
\begin{aligned}
\mathcal{L} \quad = \quad & H^\dagger i D_0 H + \text{higher dimension operators suppressed in } 1/M \\
& + \mathcal{L}_{\text{light fields}}
\end{aligned}
$$

- In the heavy-particle sector the Lagrangian is organized as an expansion in $1/M$. Contributions of higher-order operators to physical observables are suppressed by powers of E/M.
- The Lagrangian $\mathcal{L}$ may be computed at $E = 0$.
- The Lagrangian has been written in a reference frame where the heavy particle is at rest up to fluctuations of order E or smaller.

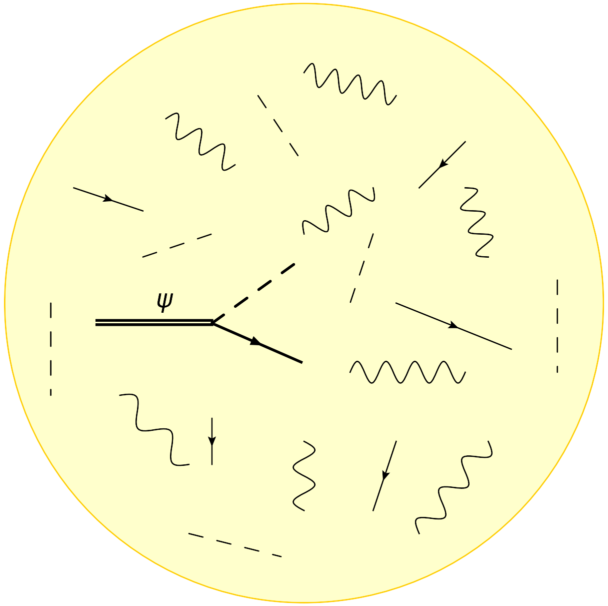
Temperature

A special case is the case of a heavy particle of mass M in a medium characterized by a temperature T such that

$$M \gg T$$

We will consider

- heavy particles in the early universe (like heavy Majorana neutrinos): the thermal bath is made of a plasma of SM particles.



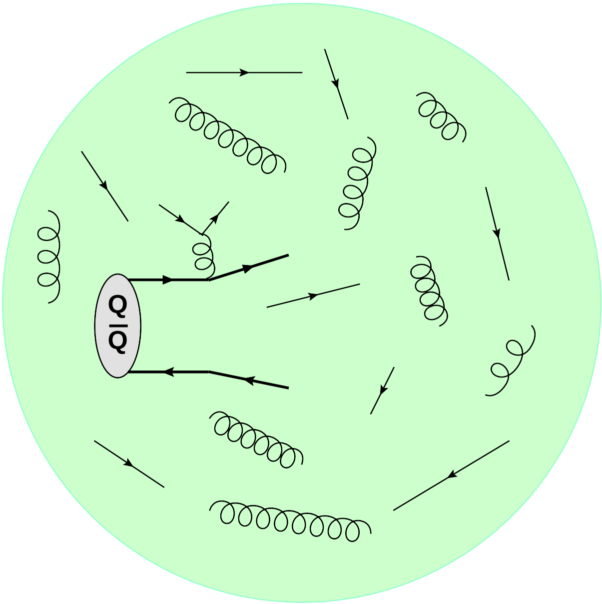
Temperature

A special case is the case of a heavy particle of mass M in a medium characterized by a temperature T such that

$$M \gg T$$

We will consider

- heavy quarkonia produced at heavy-ion colliders: the thermal bath is made of a plasma of light quarks and gluons.



Thermal non-relativistic EFTs

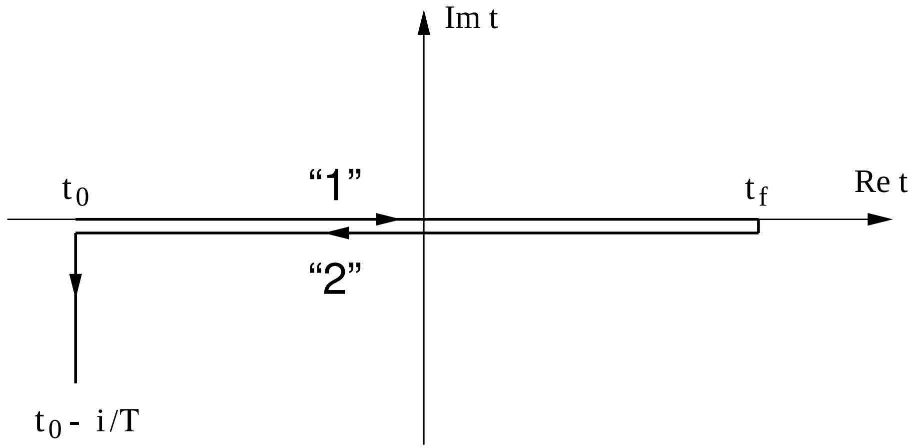
The system is described at a scale $M \gg \mu \gg T$ in terms of the EFT Lagrangian

$$\begin{aligned}\mathcal{L} &= H^\dagger i D_0 H + \text{higher dimension operators suppressed in } 1/M \\ &\quad + \mathcal{L}_{\text{light fields}}\end{aligned}$$

- In the heavy-particle sector the Lagrangian is organized as an expansion in $1/M$. Contributions of higher-order operators to physical observables are suppressed by powers of T/M.
- The Lagrangian $\mathcal{L}$ may be computed at $T = 0$, i.e. the Wilson coefficients encoding the high-energy modes may be computed in vacuum.
- The Lagrangian has been written in a reference frame where the heavy particle is at rest up to fluctuations of order T or smaller.

Real-time formalism

Temperature is introduced via the partition function.
Sometimes it is useful to work in the real-time formalism.



In real time, the degrees of freedom double ("1" and "2"), however, the advantages are

- the framework becomes very close to the one for $T = 0$ EFTs;
- in the heavy-particle sector, the second degrees of freedom, labeled "2", decouple from the physical degrees of freedom, labeled "1".

This usually leads to a simpler treatment with respect to alternative calculations in imaginary time formalism.

Real-time gauge boson propagator

- Gauge boson propagator (in Coulomb gauge):

$$\mathbf{D}_{00}^{(0)}(\vec{k}) = \frac{i}{\vec{k}^2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\mathbf{D}_{ij}^{(0)}(k) = \left(\delta_{ij} - \frac{k^i k^j}{\vec{k}^2}\right)\left\{\begin{pmatrix} \dfrac{i}{k^2 + i\epsilon} & \theta(-k^0)\,2\pi\delta(k^2) \\ \theta(k^0)\,2\pi\delta(k^2) & -\dfrac{i}{k^2 - i\epsilon} \end{pmatrix} + 2\pi\delta(k^2)\,n_{\mathrm{B}}(|k^0|)\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}\right\}$$

where

$$n_{\mathrm{B}}(k^0) = \frac{1}{e^{k^0/T} - 1}$$

Real-time heavy-particle propagator

- The free heavy-particle propagator is proportional to

$$\mathbf{S}^{(0)}(p) = \begin{pmatrix} \dfrac{i}{p^0 + i\epsilon} & 0 \\ 2\pi\delta(p^0) & \dfrac{-i}{p^0 - i\epsilon} \end{pmatrix}$$

Since $[\mathbf{S}^{(0)}(p)]_{12} = 0$, the static quark fields labeled "2" never enter in any physical amplitude, i.e. any amplitude that has the physical fields, labeled "1", as initial and final states.

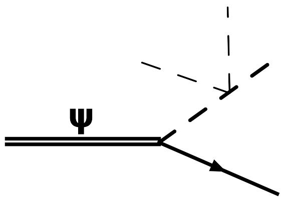
These properties hold also for interacting heavy particle(s): interactions do not change the nature ("1" or "2") of the interacting fields.

○ Brambilla Ghiglieri Vairo Petreczky PRD 78 (2008) 014017

Thermal widths at weak coupling

We will consider heavy particles interacting weakly with a weakly coupled plasma:

- a heavy Majorana neutrino in the primordial universe that interacts weakly with a plasma of massless SM particles;



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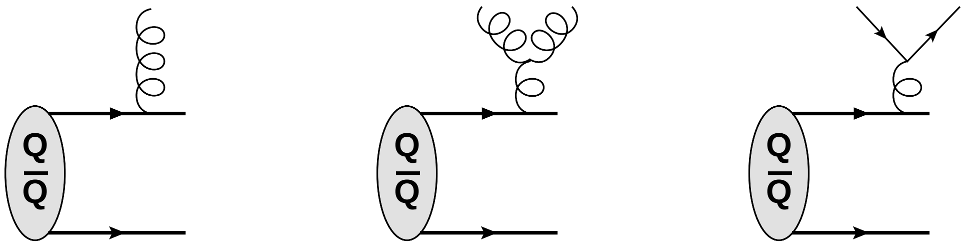
- a quarkonium formed in heavy-ion collisions of sufficiently high energy that is a Coulombic bound state interacting with a weakly coupled quark-gluon plasma.



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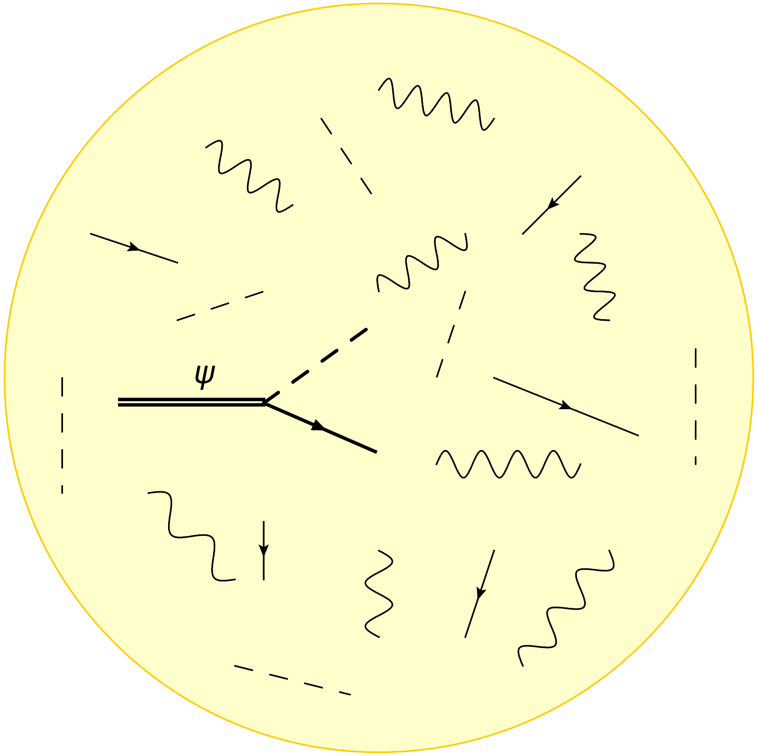
We will compute corrections to the width induced by the medium: thermal width, Γ.

Heavy Majorana neutrinos



A model for neutrino oscillation and thermal leptogenesis

We consider a heavy Majorana neutrino ψ of mass $M \gg M_W$ coupled to the SM only through a Higgs-lepton vertex:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\,\bar{\psi}\,i\partial\!\!\!/\,\psi - \frac{M}{2}\,\bar{\psi}\psi - F_f\,\bar{L}_f\tilde{\phi}P_R\psi - F_f^*\,\bar{\psi}P_L\tilde{\phi}^\dagger L_f$$

- This extension of the SM provides a model for neutrino mass generation through the seesaw mechanism.
- It also provides a model of baryogenesis through thermal leptogenesis.

∘ Minkowski PLB 67 (1977) 421
Gell-Mann Ramond Slansky CPC 790927 (1979) 315, ...
Fukugita Yanagida PLB 174 (1986) 45
Luty PRD 45 (1992) 455, ...
for a review: Drewes IJMP E22 (2013) 1330019

Baryogenesis

The observed baryons are the remnant of a small matter-antimatter asymmetry

$$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \approx 10^{-10}$$

in the early universe.

Any pre-inflationary asymmetry is diluted by inflation.

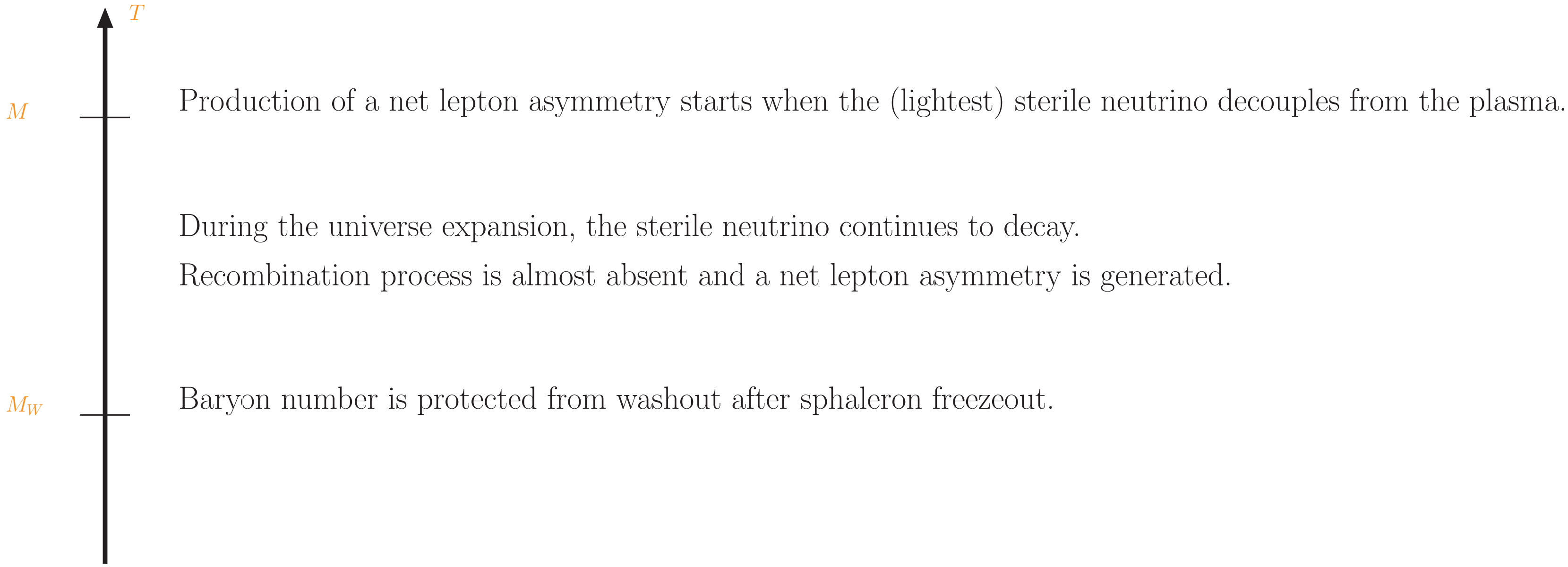
There are three necessary Sakharov conditions for a baryon asymmetry to be generated:

- baryon number violation, which is allowed in the SM by sphaleron processes (effective at $T > M_W$);
- C and CP violation, which is allowed in the SM by weak interactions and CKM phase, but too small;
- nonequilibrium, too small if induced by the expansion of the universe.

The SM cannot account for the observed asymmetry (10^{-20} vs 10^{-10}).

Baryogenesis through thermal leptogenesis

- baryon number violation: through sphaleron process, which conserve $B - L$, hence also induced by lepton number violation due to the Majorana neutrinos;
- C and CP violation: besides from the weak interaction from phases in F;
- nonequilibrium: from the Majorana neutrino production, freezeout and decay.



A key quantity for leptogenesis is the rate at which the plasma of the early universe creates Majorana neutrinos with mass M at a temperature T. This quantity is in turn related to the heavy Majorana neutrino thermal width in the plasma.

Non-relativistic Majorana neutrinos

- We consider the temperature regime

$$M \gg T \gg M_W$$

- Heavy Majorana neutrinos are non-relativistic, with momentum p^μ:

$$p^\mu = Mv^\mu + k^\mu, \qquad k^\mu \ll M \text{ (residual momentum)}$$

In kinetic equilibrium $k^\mu \sim \sqrt{MT}$; far out of equilibrium $k^\mu \sim T$.

In the reference frame where the neutrino is at rest: $v^\mu = (1, \vec{0})$.

The non-relativistic Majorana neutrino EFT

At an energy scale smaller than M and comparable with T, the low-energy modes of the Majorana neutrino are described by a field N whose effective interactions with the SM particles are encoded in the EFT Lagrangian:

$$\boxed{\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{N}}}$$

where

$$\mathcal{L}_{\text{N}} = \bar{N}\left(i\partial_0 + \frac{i\Gamma_{T=0}}{2}\right)N + \frac{\mathcal{L}^{(1)}}{M} + \frac{\mathcal{L}^{(2)}}{M^2} + \frac{\mathcal{L}^{(3)}}{M^3} + \mathcal{O}\left(\frac{1}{M^4}\right)$$

Higher-order operators are suppressed by powers of $1/M$.

$$\mathcal{L}_{\text{SM}} = \text{SM Lagrangian with unbroken SU(2)}_{\mathrm{L}}\times\text{U(1)}_{\mathrm{Y}}$$

- Biondini Brambilla Escobedo Vairo JHEP 1312 (2013) 028

Dimension 5 operator

The leading effective low-energy operator describing the decay of the Majorana neutrino into SM particles is the dimension 5 operator

$$\mathcal{L}^{(1)} = a\ \bar{N} N\, \phi^\dagger \phi$$

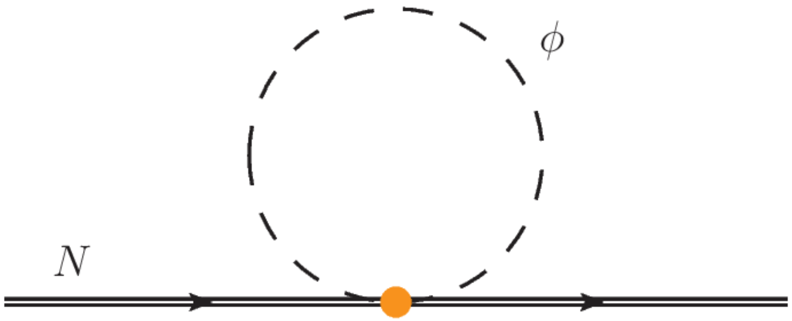
It is a neutrino-Higgs vertex, fixed at one loop by the matching condition

The Wilson coefficient a develops an imaginary part, which is

$$\mathrm{Im}\, a = -\frac{3}{8\pi} |F|^2 \lambda$$

The LO Majorana neutrino thermal width

The imaginary part of the coefficient a is the main responsible for the emergence of a heavy neutrino thermal width induced by the interaction with the plasma of SM (Higgs) particles, through the neutrino-Higgs tadpole diagram:



The thermal width is

$$\Gamma = 2\frac{\mathrm{Im}\, a}{M}\langle\phi^\dagger(0)\phi(0)\rangle_T = -\frac{|F|^2 M}{8\pi}\lambda\left(\frac{T}{M}\right)^2$$

- Salvio Lodone Strumia JHEP 1108 (2011) 116

Higher-order corrections

- We calculate them at first order in the SM couplings. We consider only Yukawa couplings with the top and neglect Yukawa couplings with other quarks and leptons.
- Thermal corrections are encoded into tadpole diagrams.
- We need to consider only operators with imaginary coefficients (tadpoles do not develop an imaginary part), coupled to bosonic operators with an even number of spatial and time derivatives (the boson propagator in the tadpole is even for space and time reflections) and to fermionic operators with an odd number of derivatives (the massless fermion propagator in the tadpole is odd for spacetime reflections).
- This implies that $\mathcal{L}^{(2)}$ does not contribute because it involves either boson fields with one derivative or fermion fields with no derivatives.

Leading momentum dependent operator

$$\frac{1}{2M^3} a \, \bar{N} \, \vec{\partial}^{\,2} \, N \, \phi^\dagger \phi$$

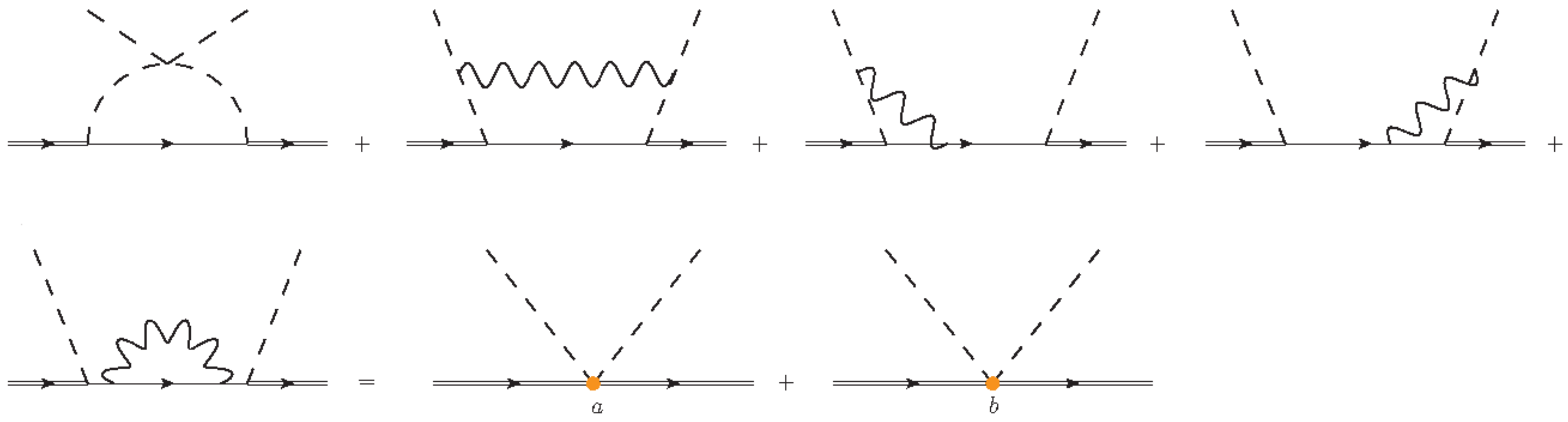
The Wilson coefficient of this operator is fixed by the relativistic dispersion relation

$$\sqrt{(M + \delta m)^2 + \vec{k}^{\,2}} = M + \delta m + \frac{\vec{k}^{\,2}}{2M} - \delta m \, \frac{\vec{k}^{\,2}}{2M^2} + \ldots$$

with $\delta m = -a \, \phi^\dagger \phi / M$.

Dimension 7 operators: Higgs couplings

$$\mathcal{L}^{(3)} = b\ \bar{N} N \left(D_0 \phi^\dagger\right)\left(D_0 \phi\right)$$

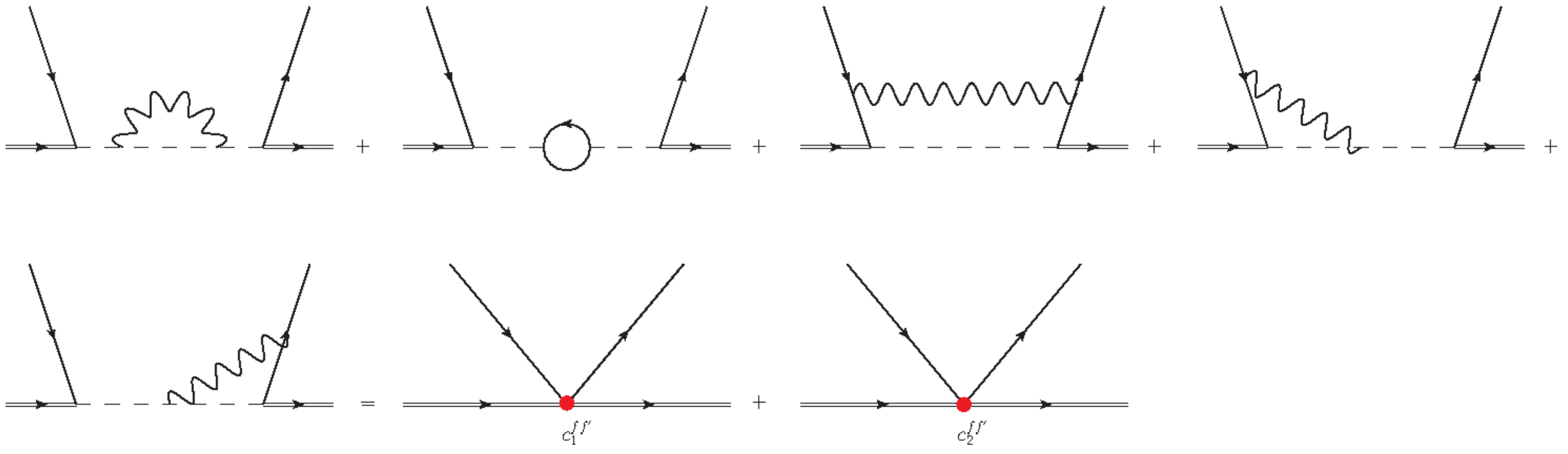


$$\mathrm{Im}\, b = -\frac{5}{32\pi}(3g^2 + g'^{\,2})|F|^2$$

Dimension 7 operators: lepton couplings

$$\mathcal{L}^{(3)} = c_1^{f\,f'} \left[\left(\bar{N} P_L \, iD_0 L_f \right) \left(\bar{L}_{f'} P_R N \right) + \left(\bar{N} P_R \, iD_0 L^c_{f'} \right) \left(\bar{L}^c_f P_L N \right) \right]$$

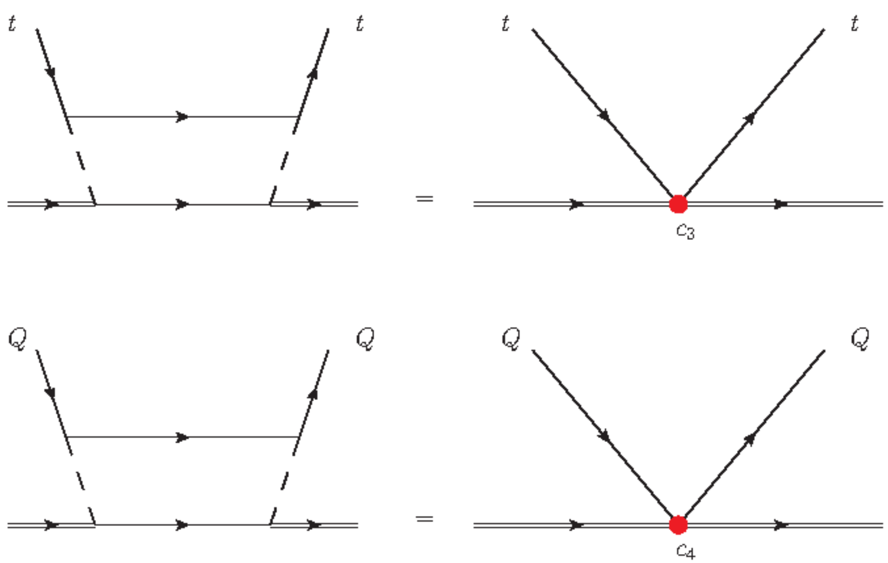
$$+ c_2^{f\,f'} \left[\left(\bar{N} P_L \, \gamma_\mu \gamma_\nu \, iD_0 L_f \right) \left(\bar{L}_{f'} \, \gamma^\nu \gamma^\mu \, P_R N \right) + \left(\bar{N} P_R \, \gamma_\mu \gamma_\nu \, iD_0 L^c_{f'} \right) \left(\bar{L}^c_f \, \gamma^\nu \gamma^\mu \, P_L N \right) \right]$$



$$\mathrm{Im}\, c_1^{f\,f'} = \frac{3}{8\pi} |\lambda_t|^2 F_{f'} F_f^* - \frac{3}{16\pi} (3g^2 + g'^{\,2}) F_{f'} F_f^*, \quad \mathrm{Im}\, c_2^{f\,f'} = \frac{1}{384\pi} (3g^2 + g'^{\,2}) F_{f'} F_f^*$$

Dimension 7 operators: quark couplings

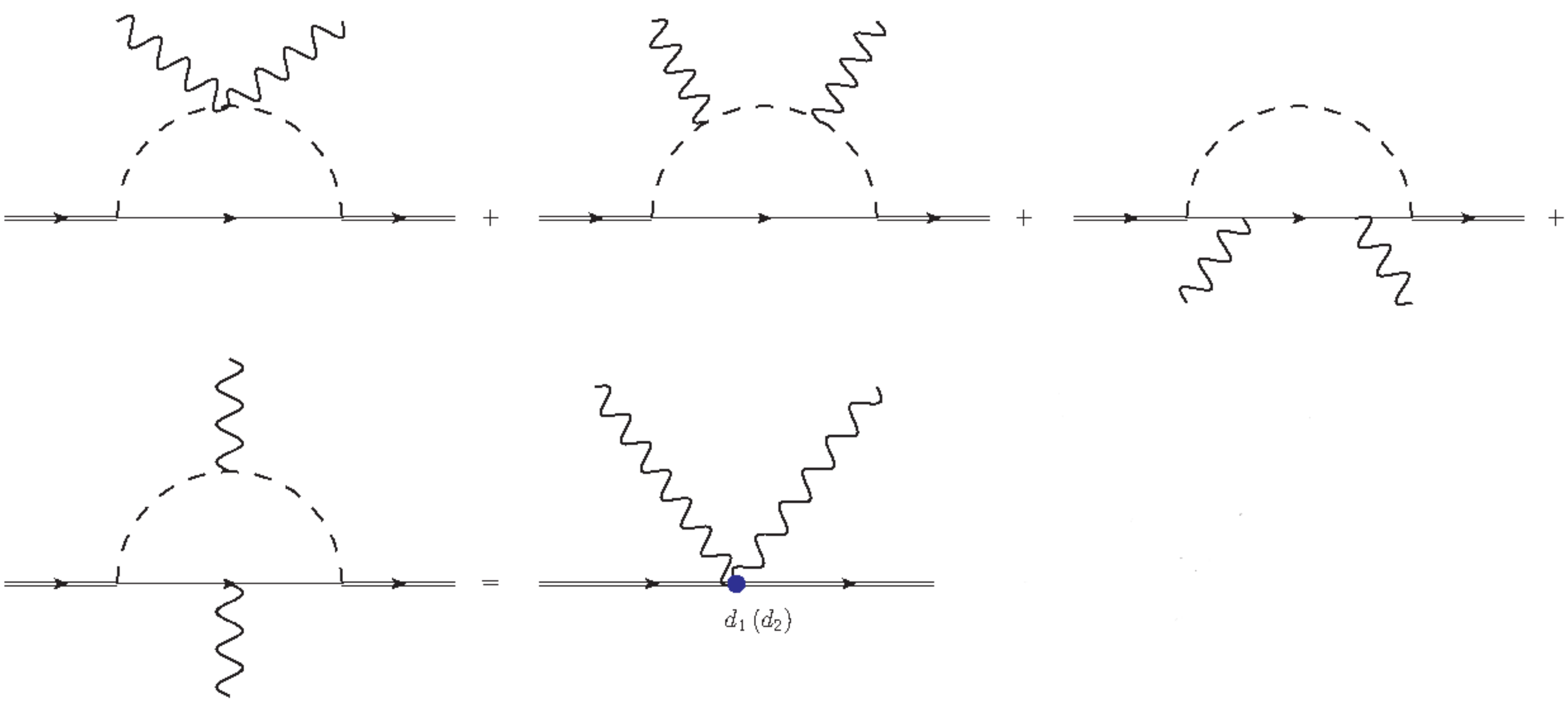
$$\mathcal{L}^{(3)} = c_3\ \bar{N}N\ (\bar{t}P_L\gamma_0\, iD_0 t) + c_4\ \bar{N}N\ \left(\bar{Q}P_R\gamma_0\, iD_0 Q\right)$$



$$\mathrm{Im}\, c_3 = \frac{1}{24\pi}|\lambda_t|^2|F|^2, \qquad \mathrm{Im}\, c_4 = \frac{1}{48\pi}|\lambda_t|^2|F|^2$$

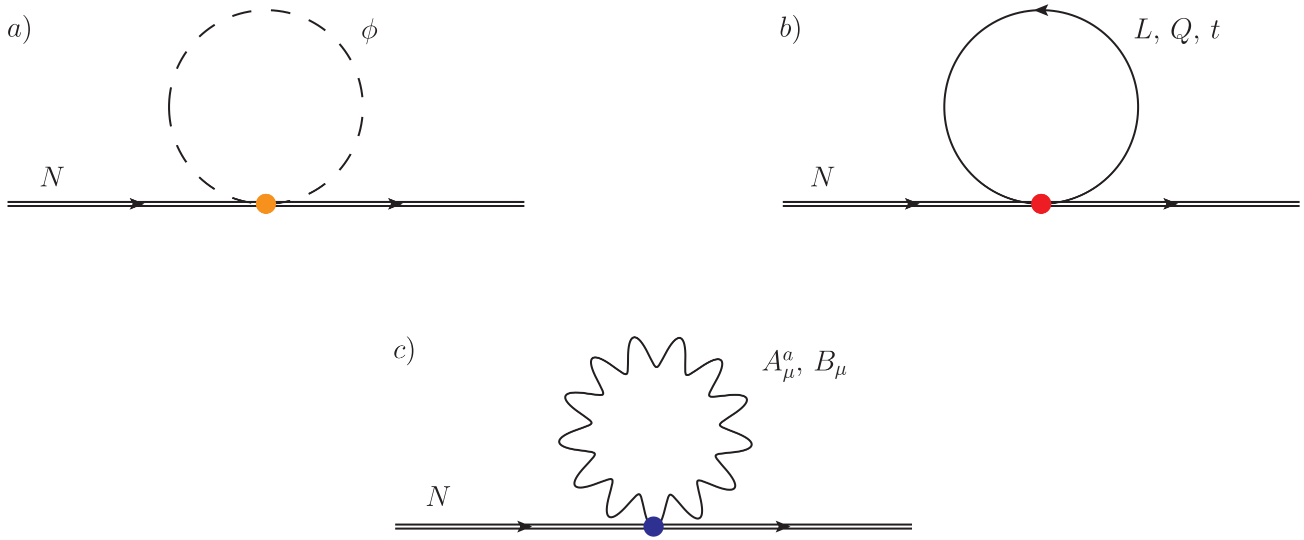
Dimension 7 operators: gauge couplings

$$\mathcal{L}^{(3)} = -d_1\ \bar{N}NW^a_{\alpha 0}W^{a\,\alpha 0}\ - d_2\ \bar{N}NF_{\alpha 0}F^{\alpha 0}$$



$$\mathrm{Im}\,d_1 = -\frac{1}{96\pi}g^2|F|^2, \qquad \mathrm{Im}\,d_2 = -\frac{1}{96\pi}g'^{\,2}|F|^2$$

The NLO Majorana neutrino thermal width

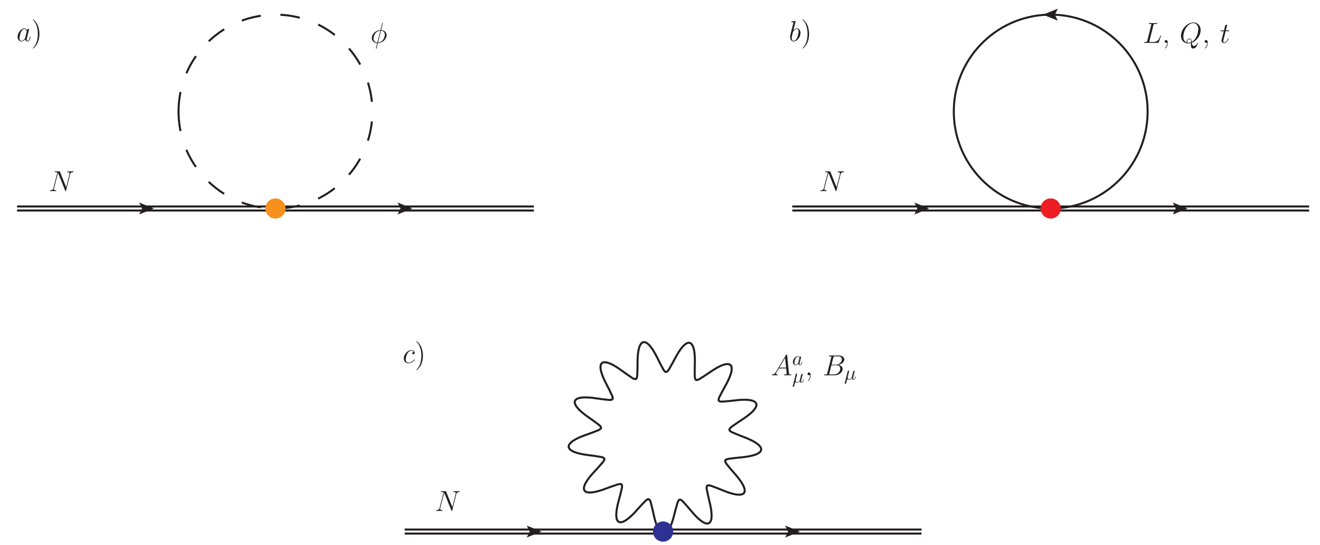


$$
\Gamma = 2\frac{\mathrm{Im}\,a}{M}\left(1-\frac{\vec{k}^{\,2}}{2M^2}\right)\langle \phi^\dagger(0)\phi(0)\rangle_T + 2\frac{\mathrm{Im}\,b}{M^3}\langle \partial_0\phi^\dagger(0)\partial_0\phi(0)\rangle_T
$$

$$
-\left(\frac{\mathrm{Im}\,c_1^{ff'}}{2M^3}+\frac{2\mathrm{Im}\,c_2^{ff'}}{M^3}\right)\langle \bar{L}_{f'}(0)\gamma^0 iD_0 L_f(0)\rangle_T + 2\frac{\mathrm{Im}\,c_3}{M^3}\langle \bar{t}(0)P_L\gamma^0 iD_0 t(0)\rangle_T
$$

$$
+2\frac{\mathrm{Im}\,c_4}{M^3}\langle \bar{Q}(0)P_R\gamma^0 iD_0 Q(0)\rangle_T + 2\frac{\mathrm{Im}\,d_1}{M^3}\langle W^a_{0i}(0)W^a_{0i}(0)\rangle_T + 2\frac{\mathrm{Im}\,d_2}{M^3}\langle F_{0i}(0)F_{0i}(0)\rangle_T
$$

The NLO Majorana neutrino thermal width

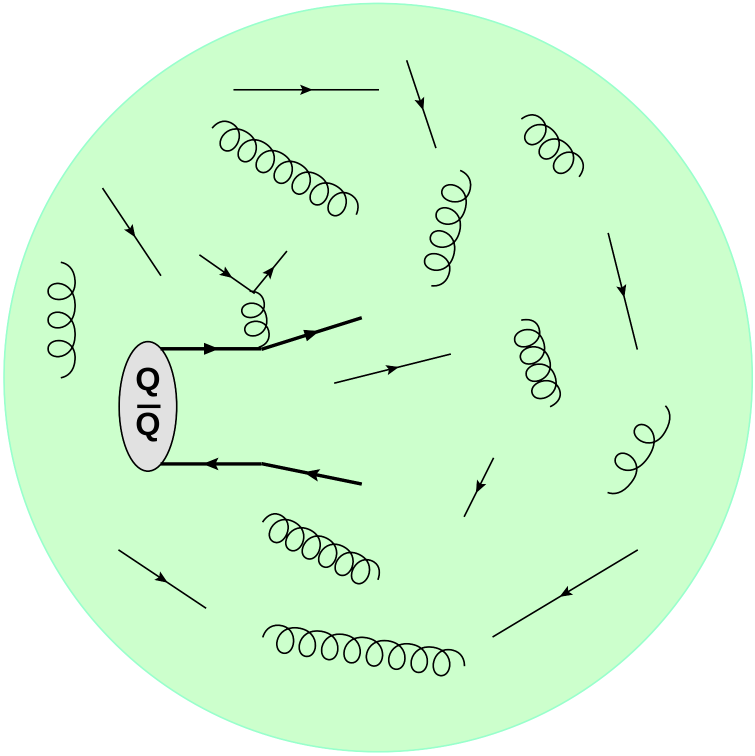


$$\Gamma = \frac{|F|^2 M}{8\pi}\left[-\lambda\left(\frac{T}{M}\right)^2 + \frac{\lambda}{2}\frac{\vec{k}^{\,2}\,T^2}{M^4} - \frac{\pi^2}{80}\left(3g^2 + g'^{\,2}\right)\left(\frac{T}{M}\right)^4 - \frac{7\pi^2}{60}|\lambda_t|^2\left(\frac{T}{M}\right)^4\right]$$

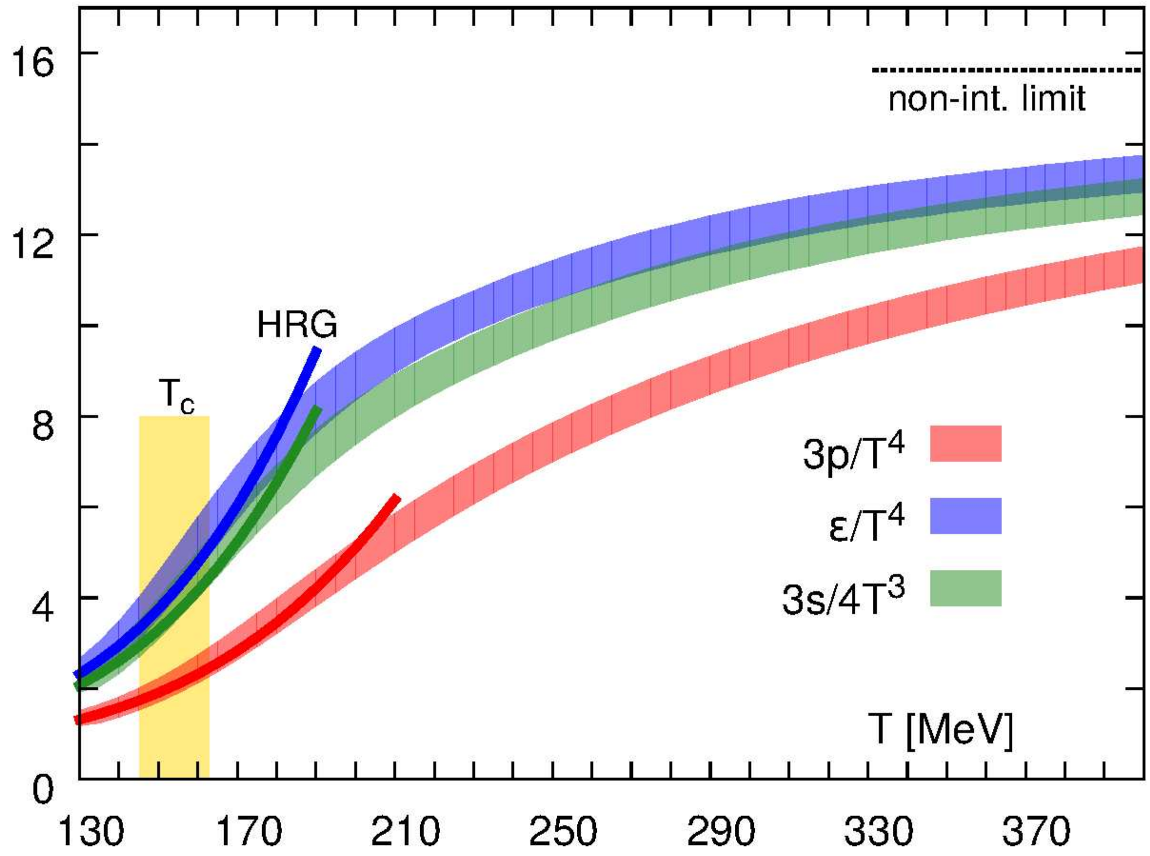
- Laine Schröder JHEP 1202 (2012) 068

  Biondini Brambilla Escobedo Vairo JHEP 1312 (2013) 028

Heavy quarkonia



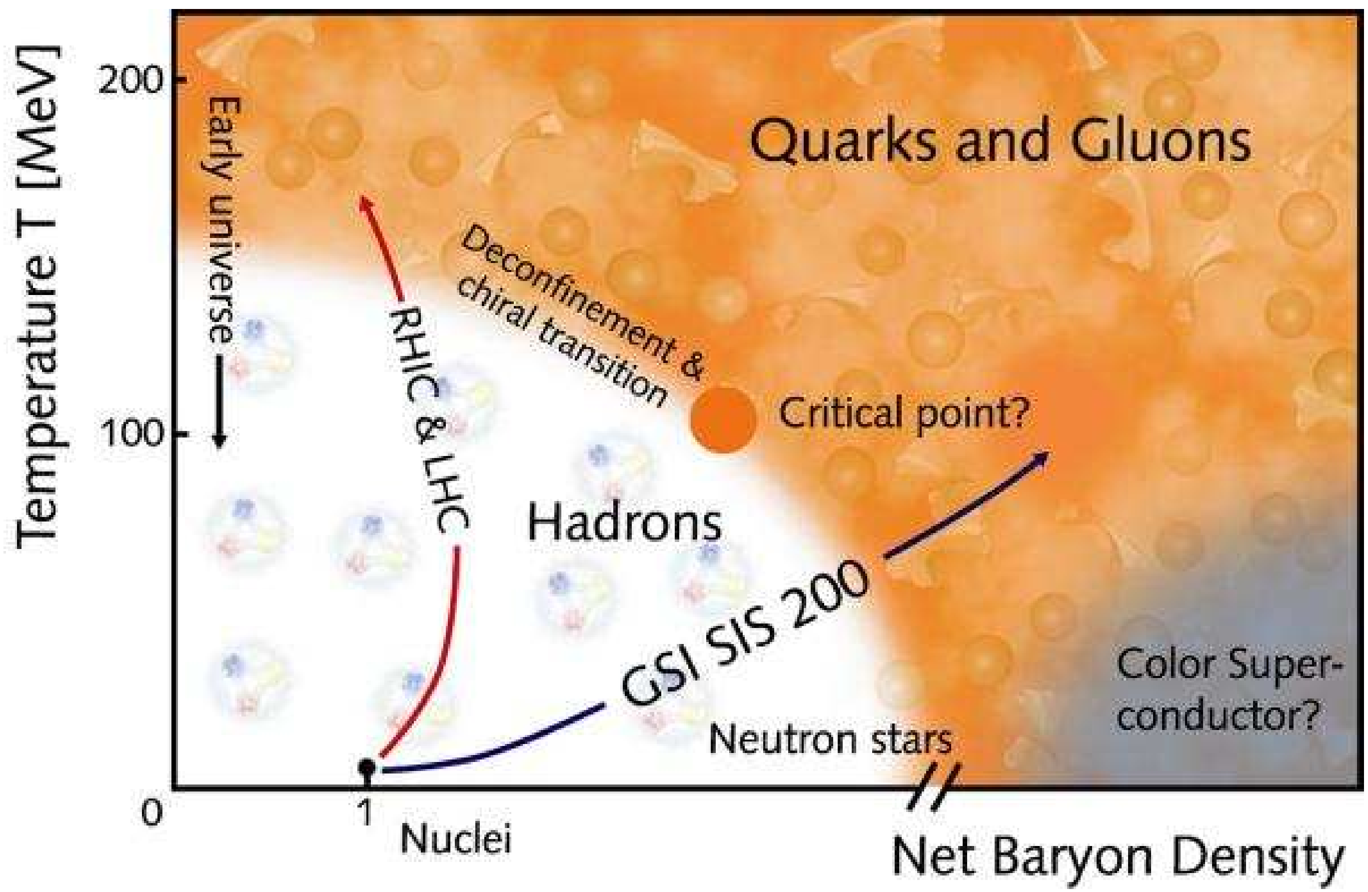
Colour deconfinement



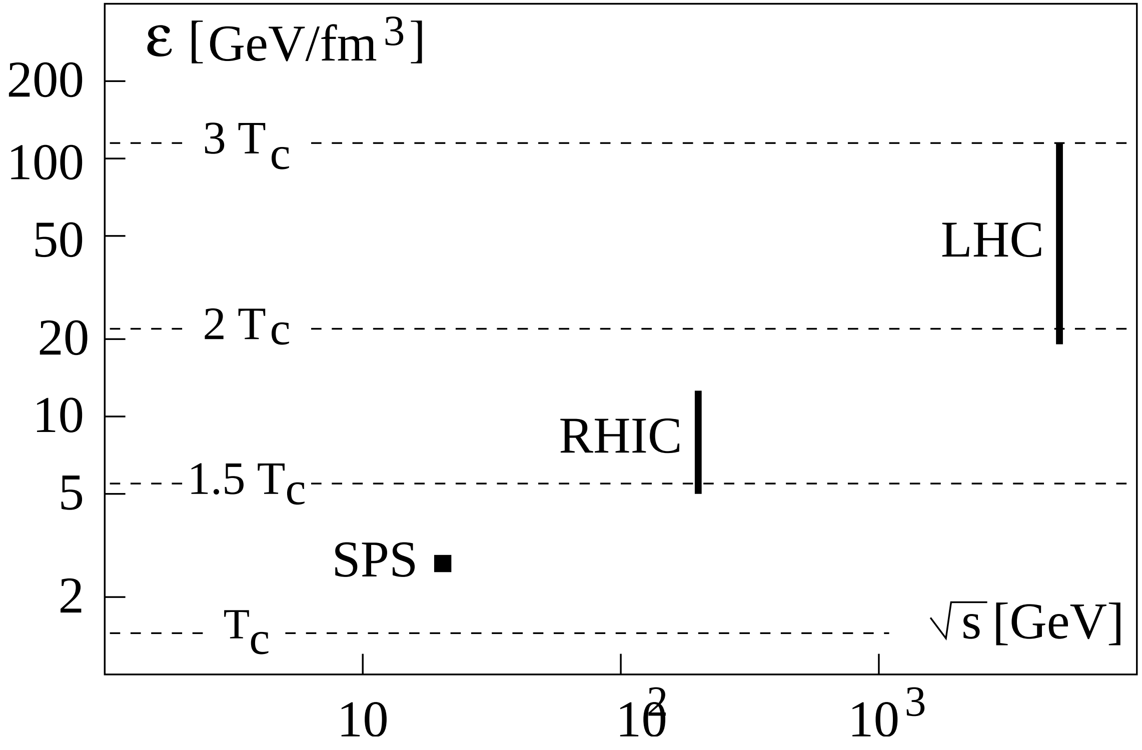
Transition from hadronic matter to a plasma of deconfined quarks and gluons happening at some critical temperature $T_c = 154 \pm 9$ MeV as studied in finite temperature lattice QCD.

○ Wuppertal-Budapest JHEP 1009 (2010) 073, HotQCD PRD 90 (2014) 094503

QCD phase diagram

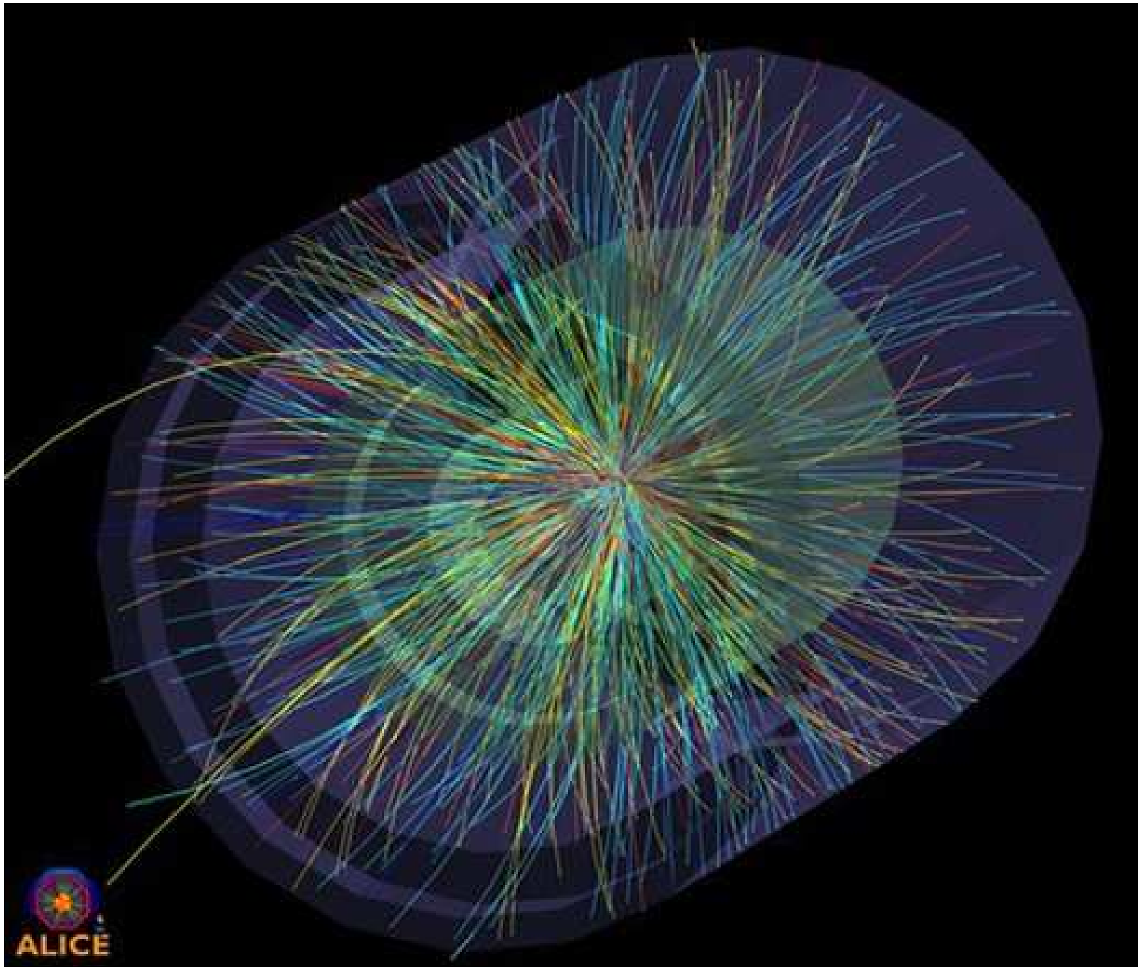


Heavy-ion experiments



High energy densities and temperatures $> T_c$ as explored by the heavy-ion experiments at RHIC and LHC.

Heavy-ion experiments

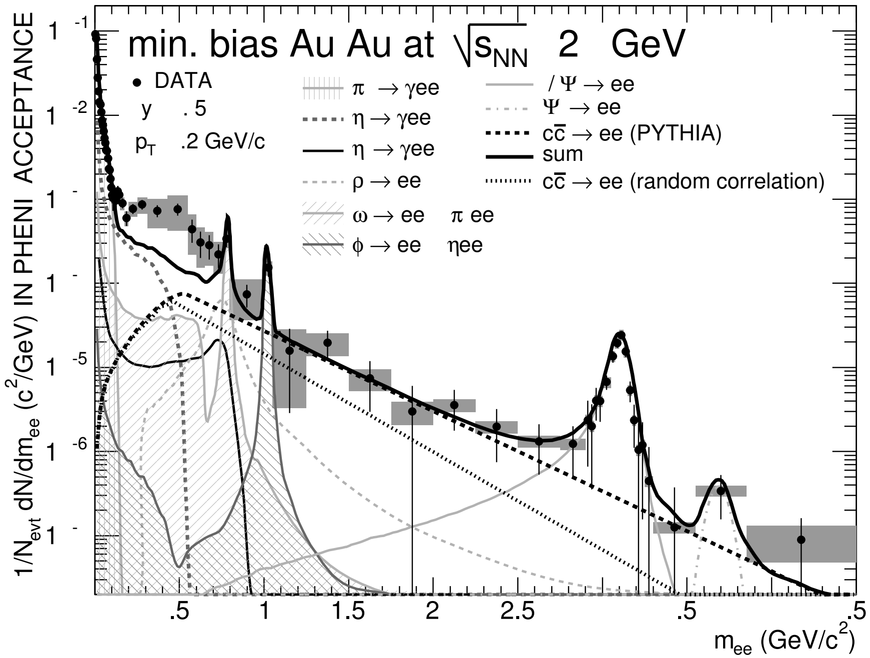


We need probes to identify the state of matter (temperature, ...) which is formed.

Quarkonium as a quark-gluon plasma probe

In 1986, Matsui and Satz suggested quarkonium as an ideal quark-gluon plasma probe.

- Heavy quarks are formed early in heavy-ion collisions: $1/M \sim 0.1$ fm $\ll 1$ fm.
- Heavy quarkonium formation will be sensitive to the medium.
- The dilepton signal makes the quarkonium a clean experimental probe.



Scales

Quarkonium being a composite system is characterized by several energy scales, these in turn may be sensitive to thermodynamical scales smaller than the temperature:

- the scales of a non-relativistic bound state
  (v is the relative heavy-quark velocity; $v \sim \alpha_{\rm s}$ for a Coulombic bound state):
  M (mass),
  Mv (momentum transfer, inverse distance),
  Mv^2 (kinetic energy, binding energy, potential V), ...

- the thermodynamical scales:
  πT (temperature),
  m_D (Debye mass, i.e. screening of the chromoelectric interactions), ...

The non-relativistic scales are hierarchically ordered: $M \gg Mv \gg Mv^2$
We assume this to be also the case for the thermodynamical scales: $\pi T \gg m_D$

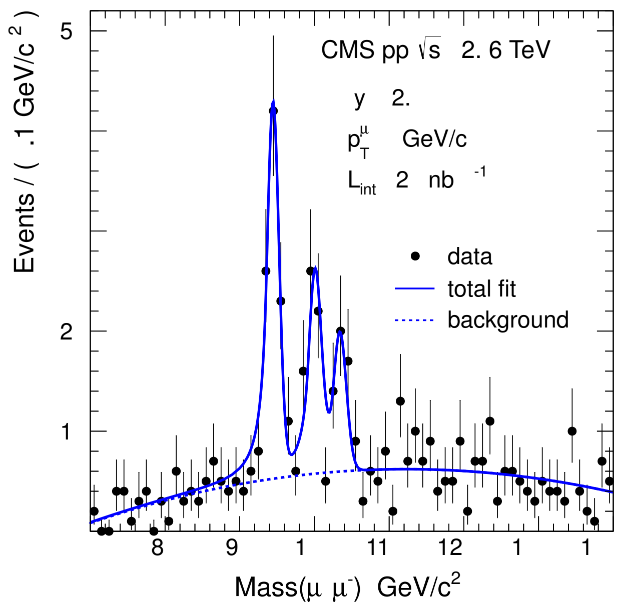
$\Upsilon(1S)$ scales

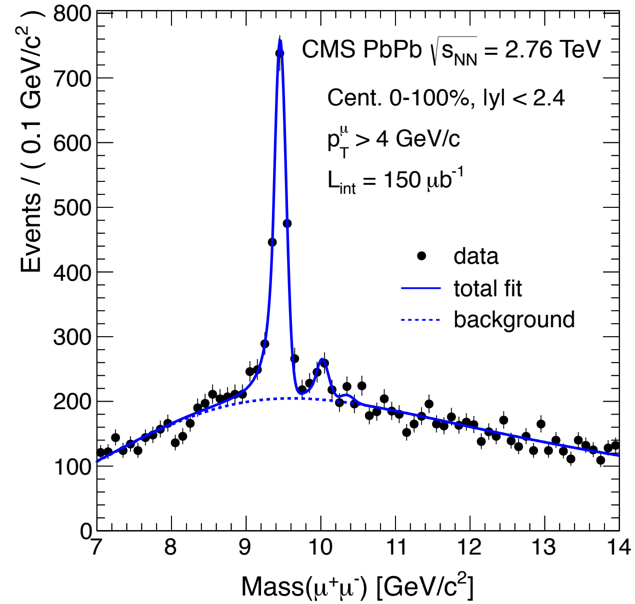
A weakly coupled quarkonium possibly produced in a weakly coupled plasma is the bottomonium ground state $\Upsilon(1S)$ produced in heavy-ion experiments at the LHC:

$$M_b \approx 5 \text{ GeV} \; > M_b\alpha_s \approx 1.5 \text{ GeV} \; > \pi T \approx 1 \text{ GeV} \; > M_b\alpha_s^2 \approx 0.5 \text{ GeV} \; \sim m_D \gtrsim \Lambda_{\rm QCD}$$

- Brambilla Escobedo Ghiglieri Soto Vairo JHEP 1009 (2010) 038
  Vairo AIP CP 1317 (2011) 241

Υ suppression at CMS

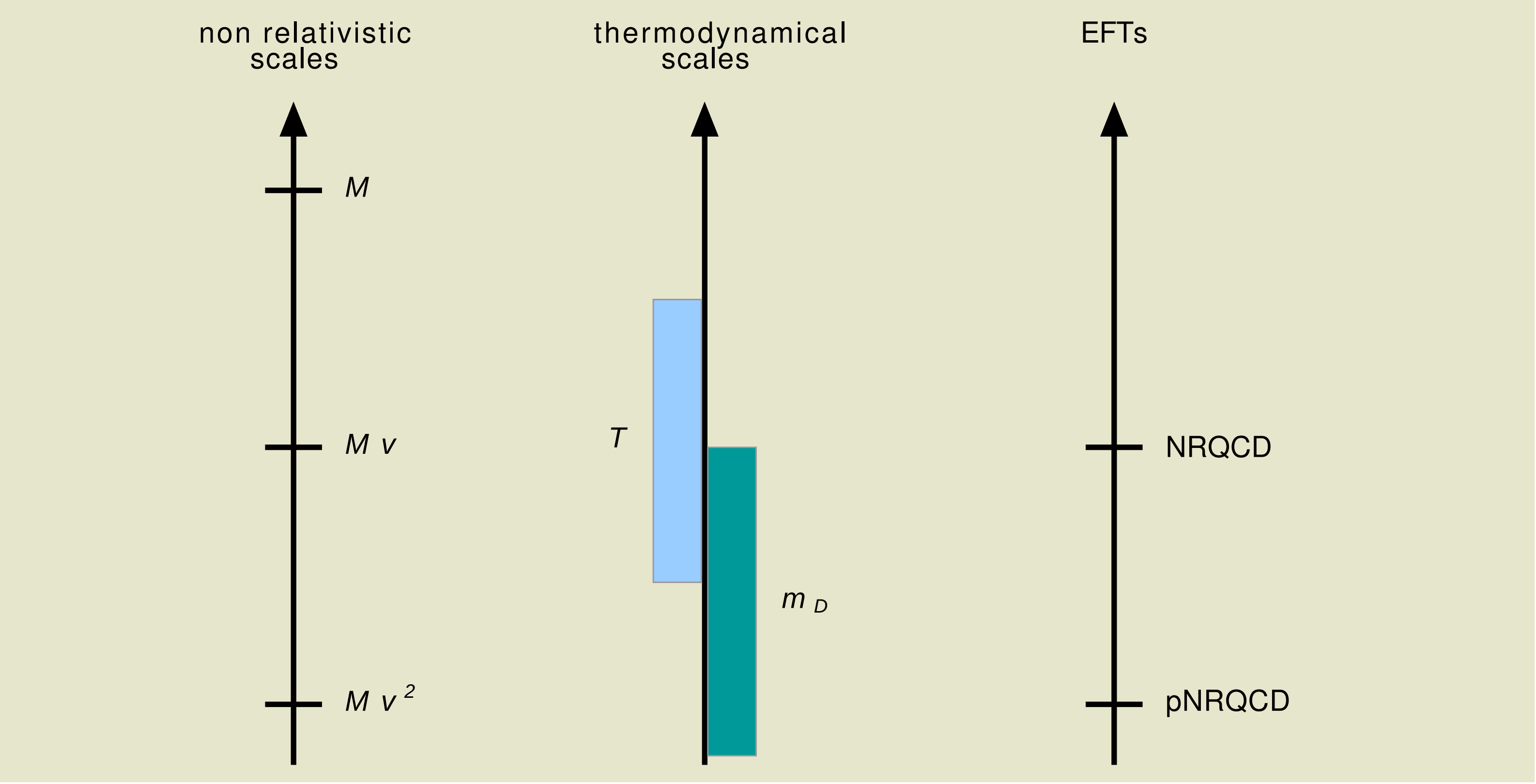




- CMS PRL 109 (2012) 222301

Non-relativistic EFTs of QCD

The existence of a hierarchy of energy scales calls for a description of the system (quarkonium at rest in a thermal bath) in terms of a hierarchy of EFTs.



For larger temperatures the quarkonium does not form.

NRQCD

NRQCD is obtained by integrating out modes associated with the scale M and possibly with thermal scales larger than Mv.

- The Lagrangian is organized as an expansion in $1/M$:

$$\mathcal{L} = \psi^\dagger \left(iD_0 + \frac{\mathbf{D}^2}{2M} + \dots \right) \psi + \chi^\dagger \left(iD_0 - \frac{\mathbf{D}^2}{2M} + \dots \right) \chi + \dots \\ + \mathcal{L}_{\text{light}}$$

ψ (χ) is the field that annihilates (creates) the (anti)fermion.

◦ Caswell Lepage PLB 167 (1986) 437
Bodwin Braaten Lepage PRD 51 (1995) 1125

pNRQCD

pNRQCD is obtained by integrating out modes associated with the scale Mv and possibly with thermal scales larger than Mv^2.

- The degrees of freedom of pNRQCD are quark-antiquark states (color singlet S, color octet O), low energy gluons and light quarks propagating in the medium.
- The Lagrangian is organized as an expansion in $1/M$ and r:

$$\mathcal{L} = \int d^3r \, \mathrm{Tr} \left\{ \mathrm{S}^\dagger \left(i\partial_0 - \frac{\mathbf{p}^2}{M} - V_s + \dots \right) \mathrm{S} + \mathrm{O}^\dagger \left(iD_0 - \frac{\mathbf{p}^2}{M} - V_o + \dots \right) \mathrm{O} \right\}$$
$$+ \mathrm{Tr} \left\{ \mathrm{O}^\dagger \mathbf{r} \cdot g\mathbf{E} \, \mathrm{S} + \mathrm{H.c.} \right\} + \frac{1}{2} \mathrm{Tr} \left\{ \mathrm{O}^\dagger \mathbf{r} \cdot g\mathbf{E} \, \mathrm{O} + \mathrm{c.c.} \right\} + \cdots$$
$$+ \mathcal{L}_{\mathrm{light}}$$

- At leading order in r, the singlet S satisfies a Schrödinger equation.
  The explicit form of the potential depends on the version of pNRQCD.

○ Pineda Soto NP PS 64 (1998) 428

Brambilla Pineda Soto Vairo NPB 566 (2000) 275, RMP 77 (2005) 1423

Dissociation mechanisms at LO

A key quantity for describing the observed quarkonium dilepton signal suppression is the quarkonium thermal dissociation width.

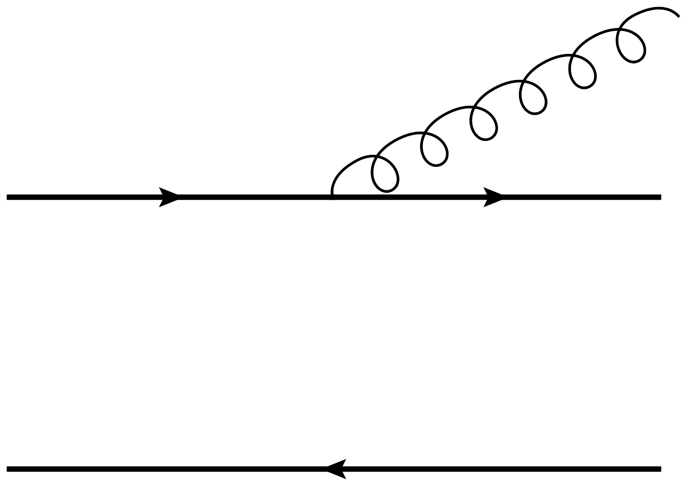
Two distinct dissociation mechanisms may be identified at leading order:

- gluodissociation,
  which is the dominant mechanism for $Mv^2 \gg m_D$;
- dissociation by inelastic parton scattering,
  which is the dominant mechanism for $Mv^2 \ll m_D$.

Beyond leading order the two mechanisms are intertwined and distinguishing between them becomes unphysical, whereas the physical quantity is the total decay width.

Gluodissociation

Gluodissociation is the dissociation of quarkonium by absorption of a gluon from the medium.

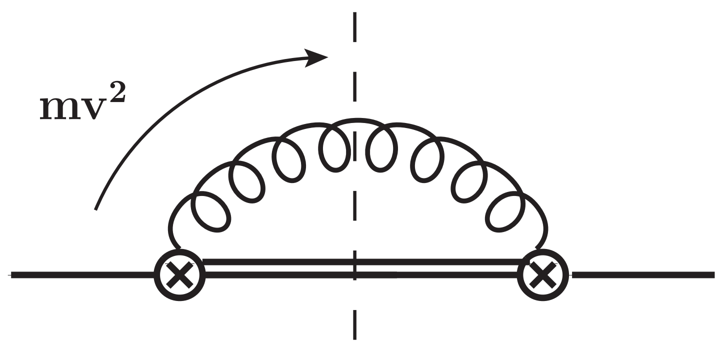


- The exchanged gluon is lightlike or timelike.
- The process happens when the gluon has an energy of order Mv^2.

○ Kharzeev Satz PLB 334 (1994) 155
Xu Kharzeev Satz Wang PRC 53 (1996) 3051

Gludissociation

From the optical theorem, the gludissociation width follows from cutting the gluon propagator in the following pNRQCD diagram



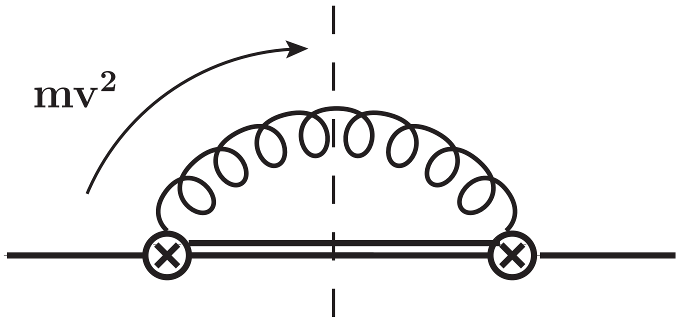
For a quarkonium at rest with respect to the medium, the width has the form

$$\Gamma_{nl} = \int_{q_{\min}} \frac{d^3q}{(2\pi)^3}\, n_{\mathrm{B}}(q)\, \sigma^{nl}_{\mathrm{gluo}}(q)\,.$$

- $\sigma^{nl}_{\mathrm{gluo}}$ is the in-vacuum cross section $(Q\overline{Q})_{nl} + g \to Q + \overline{Q}$.
- Gludissociation is also known as singlet-to-octet break up.

○ Brambilla Ghiglieri Vairo Petreczky PRD 78 (2008) 014017

$1S$ gluodissociation at LO



The LO gluodissociation cross section for $1S$ Coulombic states is

$$\sigma^{1S}_{\mathrm{gluo\,LO}}(q) = \frac{\alpha_{\mathrm{s}} C_F}{3} 2^{10} \pi^2 \rho(\rho+2)^2 \frac{E_1^4}{M q^5} \left(t(q)^2 + \rho^2\right) \frac{\exp\left(\frac{4\rho}{t(q)} \arctan\left(t(q)\right)\right)}{e^{\frac{2\pi\rho}{t(q)}} - 1}$$

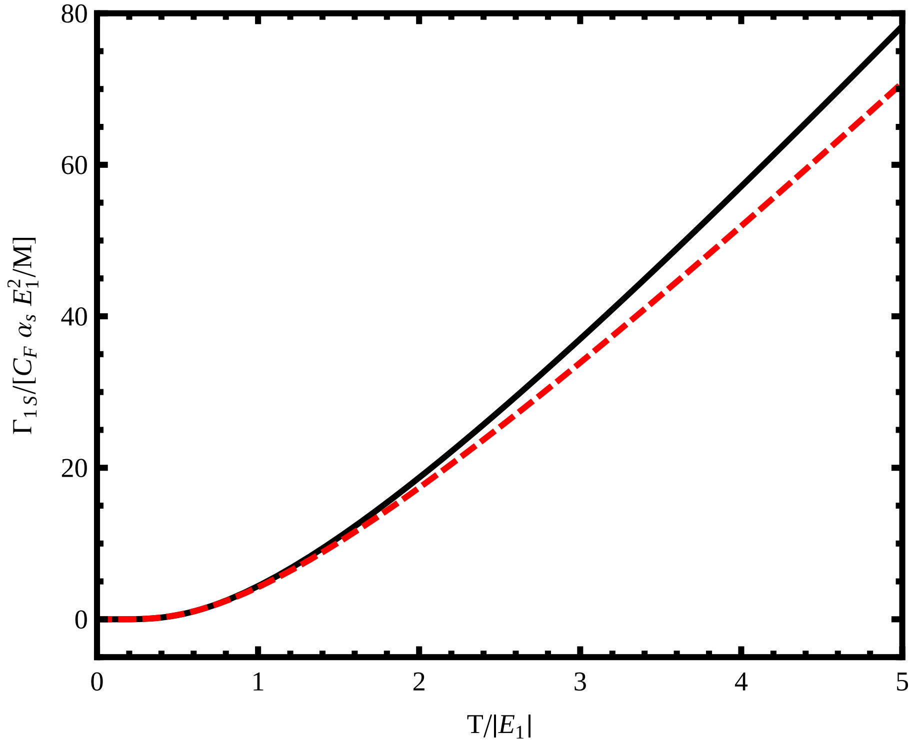
where $\rho \equiv 1/(N_c^2 - 1)$, $t(q) \equiv \sqrt{q/|E_1| - 1}$ and $E_1 = -M C_F^2 \alpha_{\mathrm{s}}^2/4$.

○ Brambilla Escobedo Ghiglieri Vairo JHEP 1112 (2011) 116
Brezinski Wolschin PLB 707 (2012) 534

The Bhanot–Peskin approximation corresponds to the large N_c limit, i.e. to neglecting final state interactions (the rescattering of a $Q\overline{Q}$ pair in a color octet configuration).

○ Peskin NPB 156 (1979) 365, Bhanot Peskin NPB 156 (1979) 391

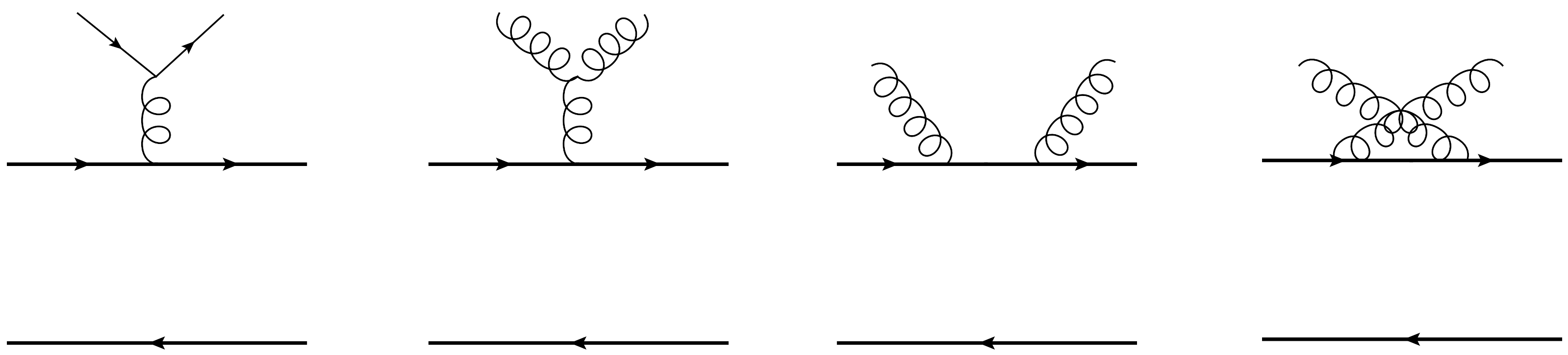
Gluodissociation width vs Bhanot–Peskin width



- Brambilla Escobedo Ghiglieri Vairo JHEP 1112 (2011) 116

Dissociation by inelastic parton scattering

Dissociation by inelastic parton scattering is the dissociation of quarkonium by scattering with gluons and light-quarks in the medium.



○ Grandchamp Rapp PLB 523 (2001) 60, NPA 709 (2002) 415

- The exchanged gluon is spacelike.
- External thermal gluons are transverse.
- In the NRQCD power counting, each external transverse gluon is suppressed by T/M.

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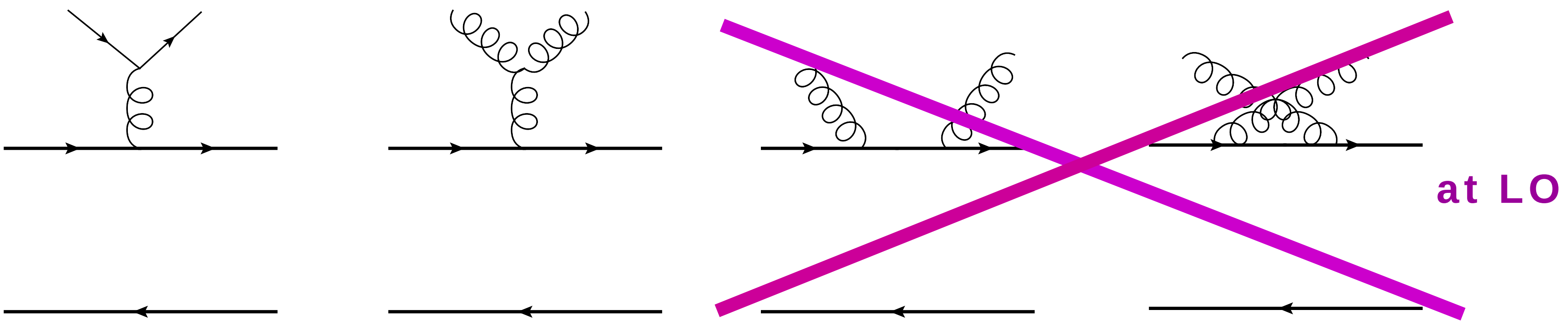

○ Grandchamp Rapp PLB 523 (2001) 60, NPA 709 (2002) 415

- The exchanged gluon is spacelike.
- External thermal gluons are transverse.
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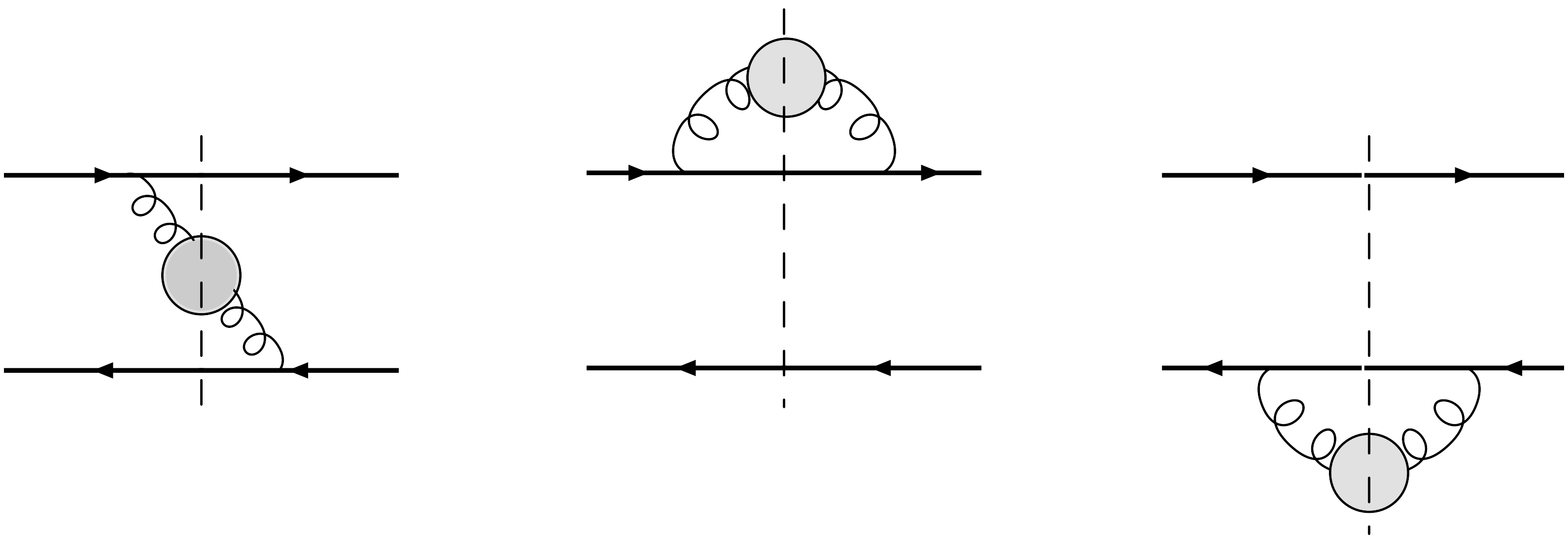
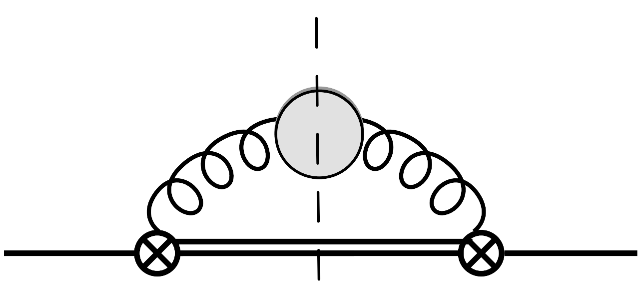
Dissociation by inelastic parton scattering

From the optical theorem, the thermal width follows from cutting the gluon self-energy in the following NRQCD diagrams (momentum of the gluon $\gtrsim Mv$)



and/or pNRQCD diagram (momentum of the gluon $\ll Mv$)



- Dissociation by inelastic parton scattering is also known as Landau damping.

Dissociation by inelastic parton scattering

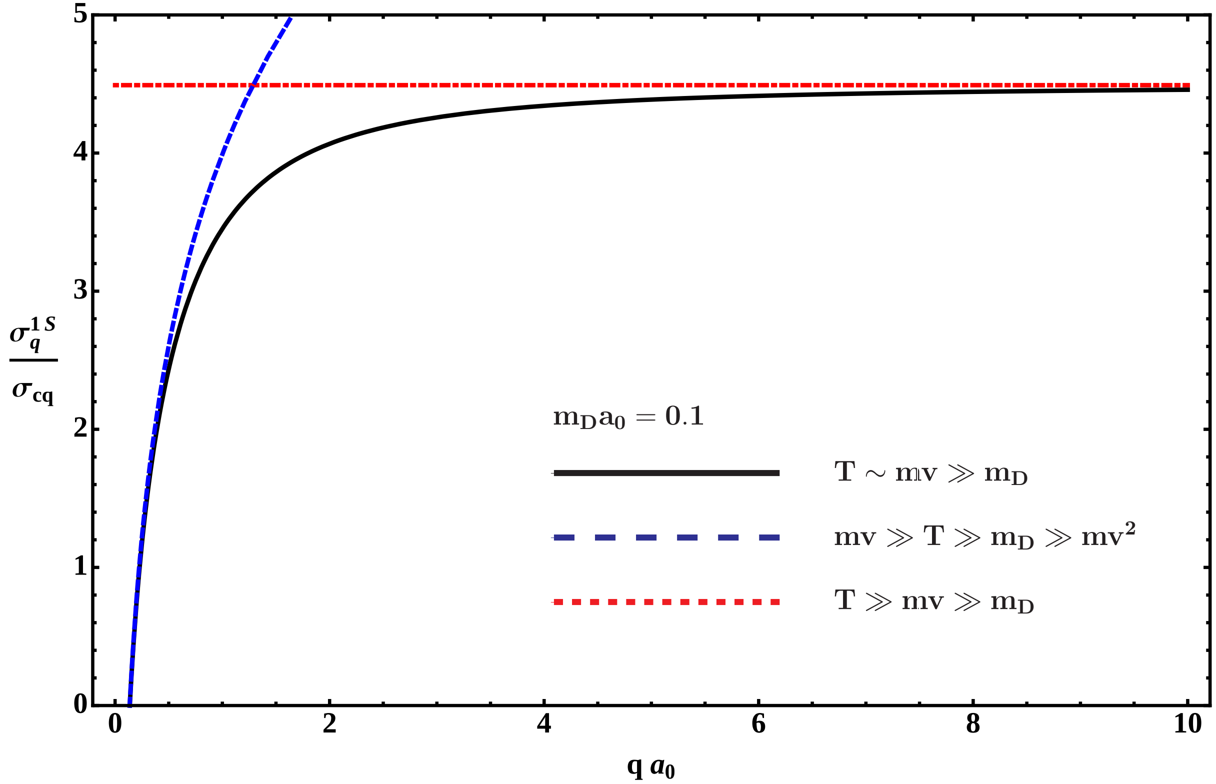
For a quarkonium at rest with respect to the medium, the thermal width has the form

$$\Gamma_{nl} = \sum_p \int_{q_{\rm min}} \frac{d^3q}{(2\pi)^3} \, f_p(q) \, [1 \pm f_p(q)] \, \sigma_p^{nl}(q)$$

where the sum runs over the different incoming light partons and $f_g = n_{\rm B}$ or $f_q = n_{\rm F}$.

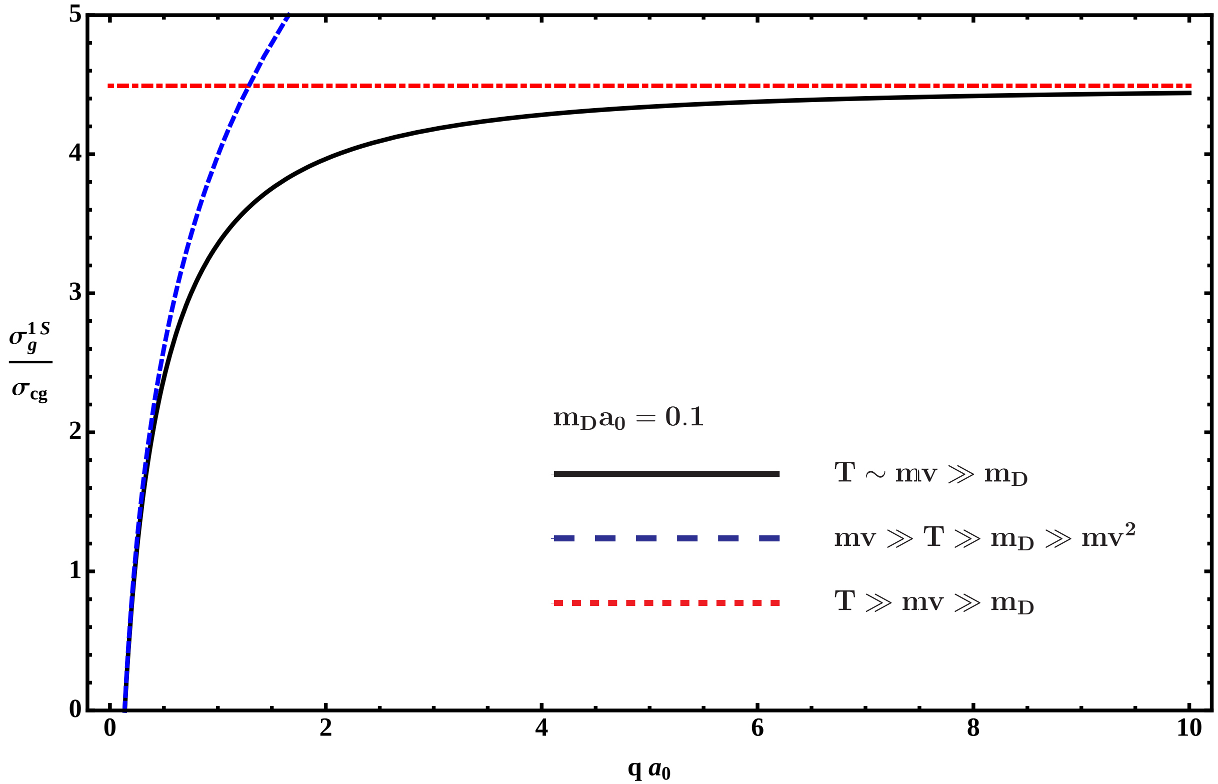
- σ_p^{nl} is the in-medium cross section $(Q\overline{Q})_{nl} + p \to Q + \overline{Q} + p$.
- The convolution formula correctly accounts for Pauli blocking in the fermionic case (minus sign).
- The formula differs from the gluodissociation formula.
- The formula differs from the one used for long in the literature, which has been inspired by the gluodissociation formula.
  - `Grandchamp Rapp PLB 523 (2001)`
    `Park Kim Song Lee Wong PRC 76 (2007) 044907, ...`

Dissociation by quark inelastic scattering



- Brambilla Escobedo Ghiglieri Vairo JHEP 05 (2013) 130

Dissociation by gluon inelastic scattering



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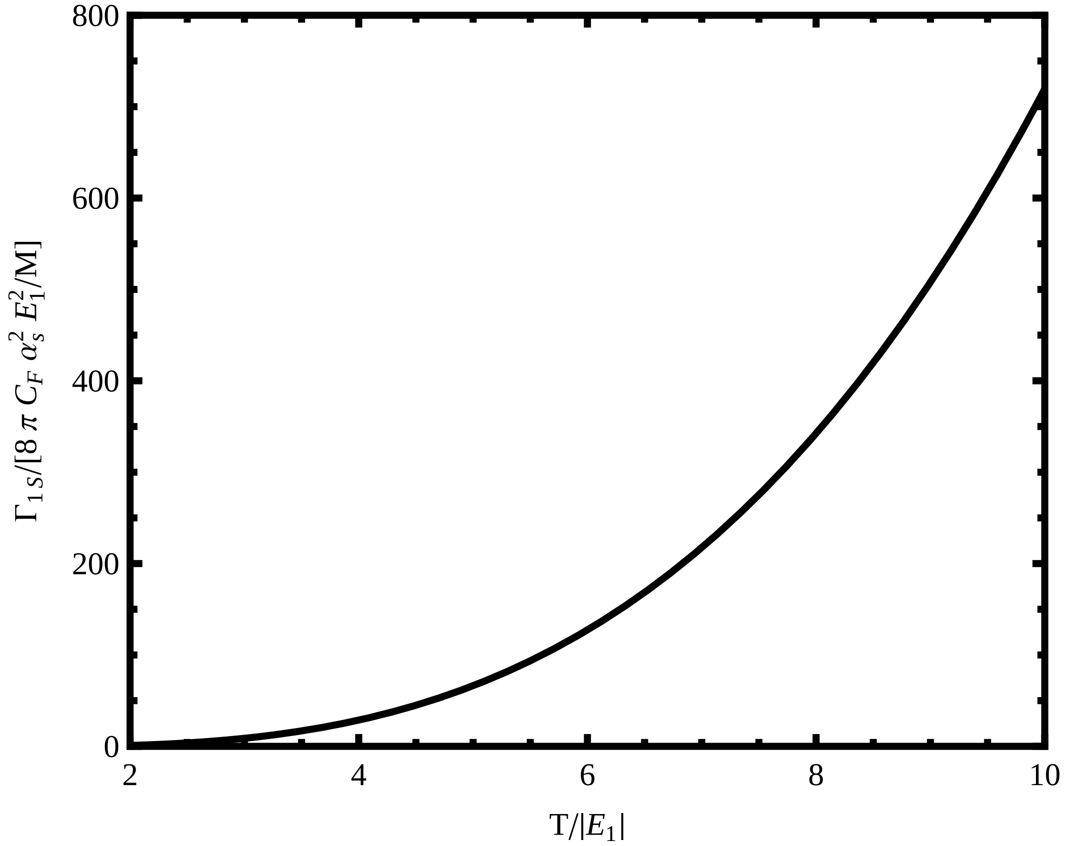
Dissociation width



$m_D a_0 = 0.5$

$|E_1|/m_D = 0.5$

$n_f = 3$

- Vairo EPJ Web Conf 71 (2014) 00135

Conclusions

In a framework that makes close contact with modern effective field theories for non relativistic particles at zero temperature, one can compute the thermal width of non-relativistic particles in a thermal bath in a systematic way.

In the situation $M \gg T$ one may organize the computation in two steps and compute the physics at the scale M as in vacuum. If other scales are larger than T, then also the physics of those scales may be computed as in vacuum. We have illustrated this on the cases of

- a heavy Majorana neutrino in the early universe plasma;
- a heavy quarkonium in a quark-gluon plasma.